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ABSTRACT. Acoustic waves have been excited in a flame seeded with potassium. We show that the amplitude of the excited wave is proportional to the frequency of a harmonic perturbation imposed on the plasma. This suggests a means of ultrasonic excitation, the limitations of which are analyzed.

I. INTRODUCTION /394**

There have been numerous observations of the fact that acoustic waves can be excited by a plasma [1]. This occurs for any natural or imposed variation of the density and temperature of the constituents in the discharge provided that these variations are not too slow and that the mean free path of neutral — neutral collisions is small compared with the plasma dimensions. Storm noise or electrical flashes are familiar examples of this phenomenon.

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(**)Numbers in the margin indicate pagination in the original foreign text.

Electrons of a plasma are usually at a temperature(*) which is greater than that of other particle types in the discharge. The electrons, therefore, transfer energy and momentum to them. In a weakly ionized gas, these transfers essentially take place to the advantage of the neutral gas components. Let H_0 and F_0 be the amounts of energy and momentum communicated to this gas per unit of volume and time. It can be shown [2] that, by using the equation for the conservation of the number of neutral particles (it is assumed that there is ionization equilibrium at any instant), the Navier-Stokes equation and the equation for energy conservation together with the gas state equation, the acoustic wave propagation equation in such a gas is given by

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \frac{\gamma - 1}{c^2}\frac{\partial H}{\partial t} + \operatorname{div} F_l \tag{1}$$

where p is the pressure fluctuation in the wave, c the phase velocity of this wave ($c^2 = \gamma kT/M$), γ the coefficient of compressibility of the gas having an atomic mass number M, temperature T. H is the first order fluctuation in H_0 and F_1 is the part with zero rotation of the first order perturbation of F_0. Expression (1) is obtained by ignoring the attenuation of the wave caused by viscosity and the thermal conductivity of the gas. Application of (1) to the plasma of a flame /395 assumes, among other things, that the temperature gradients existing in it and in the edge region can be neglected. Considering these remarks, (1) can only be considered as a first approximation of the phenomenon being studied.

It can be shown(*) that div F_1 is a small quantity (zero in any case for a homogeneous perturbation of the electron gas) and $\partial H/\partial t$ plays a dominating role in the second term of (1) where it appears as an acoustic wave source term.

The energy H_0 which the electrons communicate to the neutral particles is obviously proportional to the energy exchange during one collision between an electron and a neutral particle multiplied by the number of these collisions per unit of volume and time. In other words, all other things being equal, it is proportional to the densities of electrons and the neutral particles and to a power α of the electron temperature T_e (α depends on the shape of the variations

(*) In the plasma of a flame, the equilibrium of the various types of particles is almost established; nevertheless, it is easy to disrupt it by subjecting the flame to the action of an electric field greater than 100 volts per cm.

in the cross-section for the electron-neutral particle collisions as a function of T_e). The excitation of acoustic waves by plasma therefore becomes conceivable when the density and the electron temperature of it are modulated.

II. EXPERIMENTAL STUDY

The excitation of acoustic waves was studied with plasmas produced by a flame [3] seeded with an alkaline metal (KNO_3) as shown in Figure 1. Thus, a plasma is produced which is near to thermodynamic equilibrium which has a density of N of charged particles which can be approximately calculated using the Saha law. For a partial potassium pressure of 10^{-6}, N is approximately 10^{9} cm^{-3} at 1500° K(*).

Two tungsten pins having a diameter of 2mm are located in this flame and there is a known potential difference V_0 of about 300 volts between them. For this voltage, the collected current is on the order of 400 to 500 m A. Thus, the electron density of the flame is increased at least in the region between these pins and the thermodynamic equilibrium which was almost established there is destroyed.

On to this continuous voltage an alternating signal is superimposed having a frequency between 20 Hz and 20 k Hz. Its amplitude V_1 is approximately 200 V. Thus, the flame becomes the source of an acoustic wave and the frequency of it is the frequency of excitation across the pins. The typical level is 75 dB (reference: 2.10^{-4} μ bar).

For $V_0 = 0$ the source level is less than the audible threshold. This corresponds to the fact that the plasma is in quasi-temperature equilibrium and that the energy exchanges between the electrons and the neutral particles are zero on the average. This equilibrium is only partially destroyed by the alternating signal and cannot excite acoustic waves.

The relationship (1) shows that $\partial H/\partial t$ is the wave source term. For a harmonic modulation of V_1 at the angular frequency ω, the amplitude of the exciting source is therefore proportional to this frequency ω. This fact can easily be proven /396 by recording the sonic level emitted by the flame as a function of the modulation

(*)The temperature in the flame is measured by pyrometry of a fine metal pin immersed in the flame.

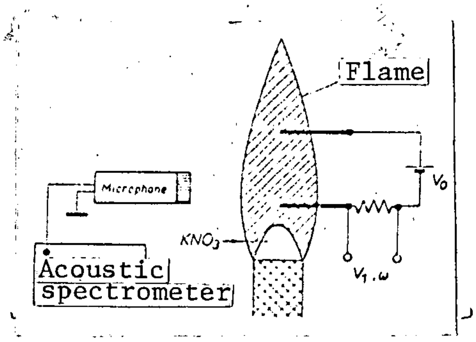

Figure 1. Arrangement for the study of acoustic wave excitation by a flame. The microphone is a condenser microphone (Brüel and Kjaer, type 4133) and has a flat response curve in the free field of almost ± 1 dB over 20 Hz. The flame is a flame of the mixture $CH_4 + O_2$.

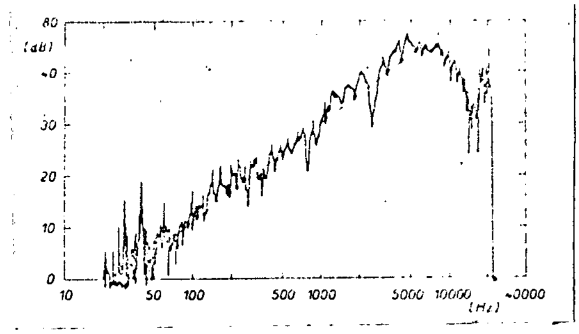

Figure 2. Sound level excited at variable frequency. The measurements were not carried out in a soundproof chamber which leads to acoustic interferences at higher frequencies (in CH_4 at 1500° K, $\lambda \simeq 6{\cdot}5$ cm at 15 k Hz, a length which is two to three times longer than the flame dimensions.)

frequency. For this a microphone is used which has a known pressure response curve as well as a pen recorder. The advancement of the paper on the recorder is controlled according to the variation in ω.

Figure 2 shows a recording obtained in this way. The irregularities observed come from the fact that the flame used is not stabilized. Nevertheless, the average value for each frequency can be plotted along a line Log p_ω = const. + Log ω. This therefore confirms that the excitation source is proportional to the modulation frequency.

III. APPLICATION

This result suggests the possibility of using a flame for exciting high frequency acoustic signals with an efficiency which increases with frequency. This point of view is justified if the flame dimensions are small compared with the acoustic wavelength. If this condition is not satisfied there will be destructive (or constructive) interference between the sonic point of the flame located at a distance of $(2n + 1)\lambda/2$ (or $n\lambda$).

Let us assume that the flame is small compared with the wavelength and let l be the plasma thickness which radiated into a given direction Π. For an arbitrary excitation frequency we can compare the emissions into Π of acoustic sources over a wavelength 1' equal to a multiple of λ. The difference 1 - 1' therefore freely radiates an acoustic wave. The larger the frequency and the smaller 1 - 1' (i.e., the remainder from the division of 1 by λ), the more the length of the plasma which is transmitting will have a tendency to decrease(*) [4].

This has the effect of diminishing the efficiency of the acoustic wave excitation by the flame plasma when one produces high frequency signals. In particular, this efficiency can be small for a sequence of values $\omega_1, \omega_2, \ldots, \omega_n \ldots$ of frequency. One is then led to reduce the plasma dimensions so that there is a displacement of the values of $\omega_1 \ldots \omega_n \ldots$, towards higher frequencies to the detrement of the average excited sound level. /397

Nevertheless, we should remark that this reduction in the emitting volume can be partially compensated by selecting a flame which has a high combustion temperature and by selecting an alkaline metal which has a smaller ionization potential, i.e., cesium.

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(*)This effect can be calculated using thd corresponding Green's function assuming averaging and measurements of the space distribution of the sound emitters.